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Cascaded Fiber Optical Parametric Amplifier with Dispersion Compensation Fiber

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ABSTRACT

Cascaded fiber optical parametric amplifier (FOPA) is believed can enhance the gain and bandwidth of the FOPA. Dispersion compensation fiber (DCF) has been proven can compensate for the dispersion of highly nonlinear fiber (HNLF). However, the effects of DCF at each stage of the cascaded FOPA is not presented. In this research, the cascaded FOPA has been demonstrated and analysed by using OptiSystem software. The cascaded FOPA has four stages of fiber with different dispersion characteristics and lengths. The gain and bandwidth of the simulation works are compared with the experimental works to see the validity of the results. The optimum value of the DCF inserted in between HNLF is discussed. The results show that the gain and bandwidth is higher when there are three pieces of DCF is inserted in cascaded FOPA. The gain and bandwidth of the FOPA achieved is 23 dB and 15 nm, respectively.

Key words: fiber optical parametric amplifier, four-wave mixing, highly nonlinear fiber, dispersion compensation fiber.

1. INTRODUCTION

A high bandwidth and long range communication is possible with the usage of optical signal [1]. Optical communication technology has effectively been developed in terms of increasing the transmission capacity by using laser beam propagating in optical fiber [2]. While signals travel along hundreds of kilometres of optical fiber, the signals attenuate and require amplifiers to amplify the signal periodically.

One of the most promising amplifier is fiber optical parametric amplifier (FOPA). It is because FOPA has an ability to amplify the power up to the S-C-L band. The other amplifier such as an erbium-doped fiber amplifier (EDFA) has its limitation to cover up those band. FOPA is based on four-wave mixing (FWM), which is a nonlinear phenomenon in an optical fiber. The new light exists when there are two or more light fed into the optical fiber. The generated light is known as an idler. Previous studies have conducted investigations regarding cascaded FOPA [3-6]. Cascaded FOPA is having the in-line configuration of two or more highly nonlinear fibers (HNLFs). In some cases, the other elements such as isolators, optical bandpass filters, and the fiber-Bragg grating are inserted in between the HNLFs [7-9]. It is believed that this element can intensify the gain or bandwidth. Besides, dispersion compensating fiber (DCF) has been demonstrated to be inserted in between the HNLFs which can act as a phase shifter [10].

In this study, the effects of dispersion compensation fiber (DCF) towards the cascaded FOPA is investigated [11]. The DCF is suitable for compensating the dispersion of the HNLF when the zero-dispersion wavelength (ZDW) is far from the pump wavelength, λ_p. In this paper, the question of the suitable value of DCF inserted to compensate the HNLF is answered. The study is further by discussing the spectrum at each stage of cascaded FOPA.

2. DISPERSION COMPESATION FIBER (DCF)

DCF is a fiber with a negative slope dispersion. The DCF is used to compensate for the HNLF dispersion by splicing the fiber into pieces with a dispersion of opposite sign at the various location of HNLF. It is believed that the resulting fiber is free from the dispersion by cascading the DCF and HNLF. In practice, it is not possible to physically realize such a composite fiber which is due to the splicing losses. Nevertheless, this theory is still practical because of the number of DCF is not very large. The ratio, ρ of the total linear phase magnitudes in the DCF and HNLF is given by:

$$\rho = -\frac{D^{'}L^{'}}{DL} \quad (1)$$

where

$$L' = ml' \qquad (2)$$

where L' is the total DCF length, m is the value of DCF inserted in between HNLF, l' is the length of DCF inserted, D and D' are dispersion for HNLF and DCF, respectively.

$\rho = 1$ corresponds to the cancellation of the total linear phase differences due to the HNLF and the DCF. But when the $\rho \geq 1$, the cancellation of linear and nonlinear phase shifts can be obtained at the particular signal wavelength.

3. METHODOLOGY

In this study, the investigation is conducted by using an Optisystem software version 14.0. The simulation setup for this case can be viewed in Fig. 1.

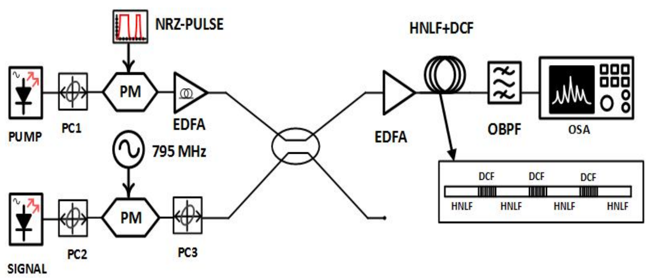

Figure 1: The simulation setup of cascaded FOPA with DCF

The CW light with a wavelength of 1542 nm acts as a pump light. The CW light is a suitable input source to achieve a broad range of communications bandwidth and by using CW laser, a substantial signal-noise-ratio (SNR) degradation can be avoided [12]. The pump light is polarized through the polarization controller. The phase modulator with an input of a non-return-to-zero (NRZ) pulse will modulate the pump light. The EDFA is used to amplify the pump light until the peak power is 11 W. The signal light also passing through the polarization controller to align the polarization of the pump and signal light. The 795 MHz RF tone is modulated by the phase modulator to suppress the SBS. The parameters of the HNLF are listed in Table 1.

Table 1: Parameters of HNLF for simulation setup

Parameter	Value
Attenuation, α	0.2 dB/km
Dispersion, D	-1.124 ps/nm.km
Effective area, A_{eff}	35 μm^2
Nonlinear Coefficient, γ	20 $W^{-1}.km^{-1}$
Length, L	40 m
Zero dispersion wavelength, λ_o	1591 nm

The value of DCF that is inserted between the HNLF is known as m. The values of m vary from 0, 1 and 3. For m = 1, the length of the DCF is 4 m with a dispersion of 16.3 ps/(nm.km). For m = 3, the length of DCF is 1.3 m for each of DCF used.

4. RESULT AND ANALYSIS

The simulation results for the cascaded FOPA with a DCF is run to observe the performance of the cascaded FOPA by using the Optisystem software. The gain and bandwidth for experimental and simulation work for each m are investigated. The gain of each m is compared to determine the best value for the insertion of a DCF between the HNLF. Fig. 2 shows the numerical, experimental and simulation gain values.

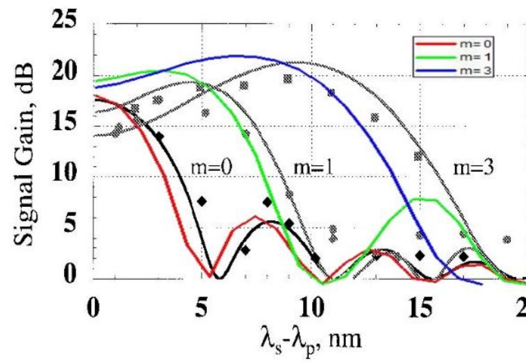

Figure 2: Numerical, experimental and simulation signal gain

From Fig. 2, the solid gray line is the theoretical values while the dotted points are the experimental values of the previous work by Marhic [11]. The red, green and blue lines are the simulation curves from the simulation. The bandwidth for m = 0 is 5 nm. The bandwidth for m = 1 is 10 nm and the bandwidth for m = 3 is 15 nm. The simulation results are almost similar to the numerical investigation that was done previously.
The simulation curves agree well with the theoretical values in determining the bandwidth of the FOPA. The gain is increased from 15 dB for m = 0 to 20 dB for m = 3. The similarity between the theoretical predictions and simulation data is because the theory assumes the losses are the same for all splices.

4.1 Cascaded FOPA with DCF, m = 0

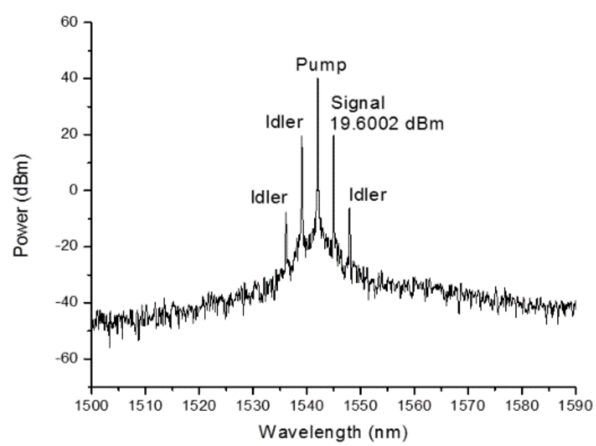

Figure 3: The first stage of cascaded FOPA for m = 0

The output power at every stage of cascaded FOPA with DCF is observed. This setup does not have a DCF inserted in between the HNLF. The signal wavelength, λ_s is 1545 nm. Fig. 3 shows the first stage of the cascaded FOPA. In this figure, the idler occurs at the wavelength of 1539 nm. The signal power is measured at each with a power of 19.6002 dBm.

After passing the first stage of the cascaded FOPA, the combined light will be fed into the second stage. Fig. 4 shows the spectrum inside the second stage. From the figure, the signal power is 22.1379 dBm.

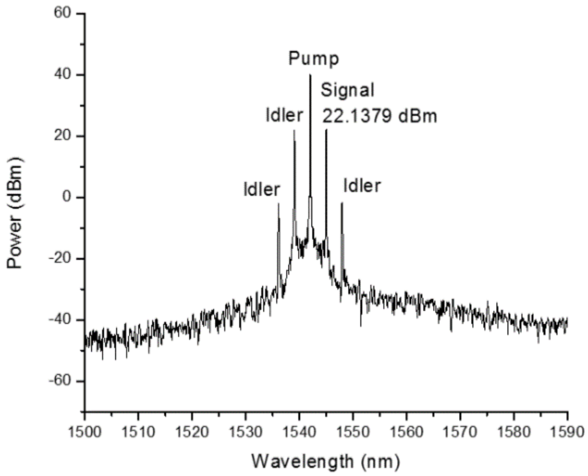

Figure 4: The second stage of cascaded FOPA for m = 0

The signal power is slightly increased from 19.6002 dBm to 22.1379 dBm. The cascaded FOPA can enhance the power even without any other elements in between the HNLF. The high signal power at the output of the cascaded FOPA provides the high gain spectrum.

Table 2 lists the pump, signal and idler power for m = 0. The pump power decreases due to the power transfer to the signal and idler. The idler power increased from the first stage to the second stage.

Table 2: Pump, signal and idler power for m = 0

Stage	Pump Power (dBm)	Signal Power (dBm)	Idler power (dBm)
1	40.0991	19.6002	19.3116
2	40.0327	22.1379	21.9728

4.2 Cascaded FOPA with DCF, m = 1

The second case is when m = 1. This setup is to analyze the dispersion compensation involves in the cascaded FOPA as the DCF is inserted in between the HNLFs. The dispersion of the HNLF and DCF is in the opposite sign. The results are observed at the output of the first HNLF, DCF and the second HNLF. The power of the signal light is measured. Fig. 5 shows the output power at each stage of the cascaded FOPA with m = 1.

The first idler is parametric to the signal wavelength, λ_s = 1545 nm. The idler wavelength, λ_i is equal to 1539 nm. This proves that the idler wavelength is the mirror image of the signal wavelength [13]. The signal power at the first stage is 19.6002 dBm as shown in Fig. 5(a).

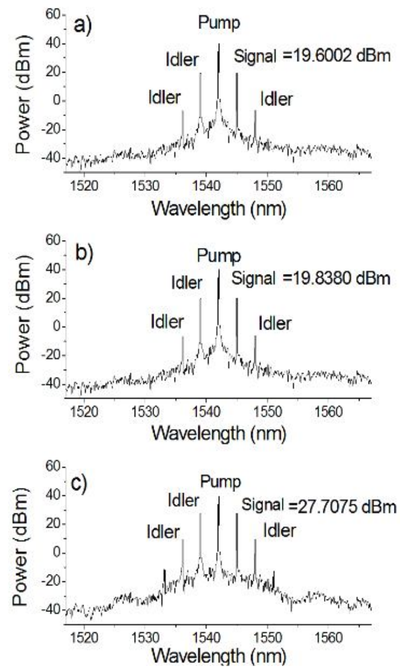

Figure 5: Output power from the first stage for m = 1

From Fig. 5(b), the signal power at the second stage is 19.8380 dBm. The amplification of power occurs in the fiber. The amplification of signal power provides a high gain as the gain is measured between the input and output power.

In Fig. 5(c), the signal power increases from 19.8380 dBm to 27.7075 dBm. There is a significant difference between the signal power at the second and third stages. It means that the DCF has successfully compensated the dispersion of HNLF. By using Equation 3.2, the value of ρ is equal to 1.45. When ρ exceeds the value of one, the cancellation of linear and nonlinear phase shift is obtained for the particular λ_s.

Table 3 tabulates the pump, signal and idler power at each stage for m = 1. The pump power is decreasing because of the energy transfer to the signal and idler. Subsequently, the power from the pump increases the signal and idler powers.

Table 3: Pump, signal and idler power for m = 1

Stage	Pump power (dBm)	Signal power (dBm)	Idler power (dBm)
1	40.0986	19.6002	19.6371
2	40.0933	19.8380	19.8750
3	39.6336	27.7075	27.7524

4.3 Cascaded FOPA with DCF, m = 3

In this setup, three DCFs are cascaded with the HNLFs. The output is measured at each stage. In this case, the optimum value of DCF that is inserted between the fiber is going analyzed. The gain for m = 3 is higher than m = 1. It shows that the gain increases as the value of DCF are added in the cascaded FOPA configuration. The signal power is analyzed at each stage to see the changes as the gain increases. It shows the signal power at every stage of the cascaded FOPA with DCF for m = 3.

From Fig. 6, the signal wavelength, λ_s is at 1545 nm. This wavelength is chosen because of the perfect phase matching in this wavelength. In addition, the peak gain spectrum also occurs at this wavelength. The idler wavelength, λ_i is at 1539 nm.

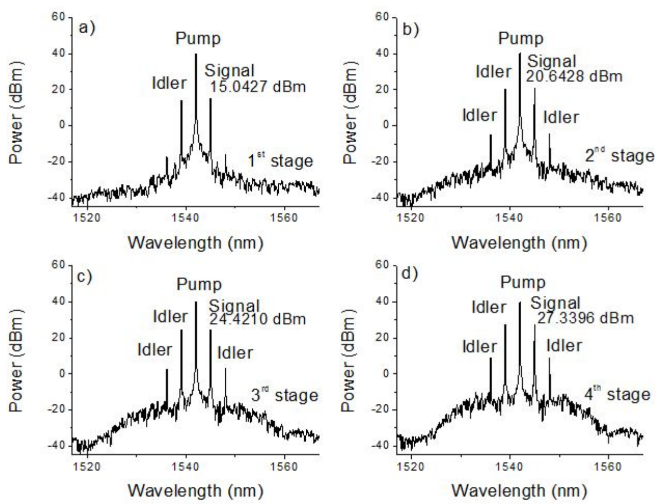

Figure 6: Output power at every stage of cascaded FOPA with DCF for m = 3

From Fig. 6(a), the signal power at the first stage is 15.0427 dBm. The signal power at the second stage is 20.6428 dBm as shown in Fig. 6(b). There is an improvement of the signal power from the first HNLF to the first DCF. The different values of dispersion from both fibers enable the signal power to amplify. The value of ρ is equal to 1.41. It means that there is a total cancellation of the linear and nonlinear phase shifts.

Next, the following stages of cascaded FOPA are observed to see the differences between the stages. The third stage, as shown in Fig. 6(c) has a signal power of 24.4210 dBm. Lastly, the signal power for the last stage is provided in Fig. 6(d) with signal power of 27.3396 dBm. The significant difference between these idler powers is due to the compensation of the DCF before the new stage. The value of ρ is still equal to 1.41 because it depends on the dispersion and length. The length and dispersion of each fiber are fixed at the same value. The number of idlers also increases from the previous stages.

The last stage also shows that amplification occurs every time the light is passing through the HNLFs after the DCFs. The DCF compensates the dispersion and is fed into the HNLF which has a higher nonlinearity that can enhance the gain by providing a greater value of idler power. The value of ρ remains at 1.41.

Table 4 shows the power at each stage of the cascaded FOPA for the pump, signal and idler power. The idler power also shows increasing values at each stage like signal power. This is because the idler is a mirror image of the signal light. The pump power, on the other hand, decreases at every stage because of the power is transferred to the signal and idler.

Table 4: Pump, signal and idler power at each stage for m = 3

Stage	Pump power (dBm)	Signal power (dBm)	Idler power (dBm)
1	40.1497	15.0427	14.1195
2	40.0758	20.6428	20.4076
3	39.9321	24.4210	24.3215
4	39.6829	27.3396	27.2855

5. CONCLUSION

In summary, pump dithering and DCF are affected by the performance of cascaded FOPA. DCF is used to compensate for the dispersion from the first fiber. The results show that the gain and bandwidth increase as the values of DCF are increased.

The results of DCF cases show that the signal and idler power at each stage increases which can be attributed to the cascaded structure.

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REFERENCES

1. A. H. Bhat, H. V. Balachandra Achar. **Dual parametric stabilization of interference and throughput in wireless sensor network - optical communication**. *International Journal of Advanced Trends in Computer Science and Engineering*, vol. 8, no. 5, pp. 1937–1945, 2019. https://doi.org/10.30534/ijatcse/2019/18852019
2. M. N. Derahman, A. R. Abdul Rahiman, M. A. Mohamed, and A. Malekmohammadi. **CNDS-rules and pattern based signal recovery for multi-level signal decision making.** *International Journal of Advanced*

Trends in Computer Science and Engineering, vol. 8, no. 1.4, pp. 356–362, 2019. https://doi.org/10.30534/ijatcse/2019/5481.42019

3. H. N. Tan, T. Inoue, K. Tanizawa, S. Petit, Y. Oikawa, S. Takasaka, T. Yagi, and S. Namiki. **Counter-dithering pump scheme for cascaded degenerate FWM based wavelength converter**. *Conf. Opt. Fiber Commun. Tech. Dig. Ser.*, pp. 31–33, 2014.
4. S. Takasaka, Y. Mimura, H. Matsuura, M. Morimoto, M. Takahashi, and R. Sugizaki. **FOPA with flat 21-dB gain and NF less than 4-dB using alternately concatenated pump-phase shifters and HNLFs.** in *Proc. Opt. Fiber Commun. Conf. Fiber Opt. Eng. Conf.*, 2013, pp. 1–3.
5. X. Ruihong, C. Yu, X. Sang, and D. Hsu. **Research on QPM and its cascaded structure applied in FOPA.** *Cybern. Inf. Technol*., vol. 16, no. 5, pp. 50–58, 2016.
6. F. N. Mohamad Salleh, N. S. Mohd Shah, N. Othman, R. Talib, M. A. Rahman. **Effect of pump dithering at each stage of cascaded fiber optical parametric amplifier.** *Telkomnika (Telecommunication Computing Electronics and Control)*, vol. 15, no. 3, pp. 1440–1445, 2017.
7. K. K. Y. Wong, K. Shimizu, K. Uesaka, G. Kalogerakis, M. E. Marhic, and L. G. Kazovsky. **Continuous-wave fiber optical parametric amplifier with 60-dB gain using a novel two-segment design**. *IEEE Photonics Technol. Lett*., vol. 15, no. 12, pp. 1707–1709, 2003.
8. H. Zhu. **Gain optimization of one-pump fiber-optical parametric amplifier with optical band-pass filter reducing the idler wave.** *Opt. Eng*., vol. 51, no. 6, p. 64301, 2012.
9. H. Zhu, B. Luo, W. Pan, L. Yan, S. Xiang, and K. Wen. **Gain enhancement of fiber optical parametric amplifier via introducing phase-shifted fiber Bragg grating for phase matching.** *J. Opt. Soc. Am. B*, vol. 29, no. 6, p.1497, 2012.
10. M. Xia, Y. Wu, S. Xia, G. Liu, H. Yang, Z. Ping, T. Wang. **Power equalization for non-degenerate cascaded phase-sensitive fiber-optic parametric amplifier.** in *Proc. 4th International Conference on Computer Science and Network Technology*, 2015, pp. 1236-1239.
11. M. E. Marhic, F. S. Yang, M. Ho, and L. G. Kazovsky. **High-nonlinearity fiber optical parametric amplifier with periodic dispersion compensation.** *J. Light. Technol*., vol. 17, no. 2, pp. 210–215, 1999. https://doi.org/10.1109/50.744225
12. F. S. Yang, M. E. Marhic, and L. G. Kazovsky. **CW fibre optical parametric amplifier with net gain and wavelength conversion efficiency >1.** *Electron. Lett*., vol. 32, no. 25, pp. 2336–2338, 1996.
13. J. Hansryd, P. A. Andrekson, M. Westlund, J. Li, and P. O. Hedekvist. **Fiber-based optical parametric amplifiers and their applications.** *IEEE J. Sel. Top. Quantum Electron*., vol. 8, no. 3, pp. 506–520, 2002.